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δ-layer quenched high-frequency conductivity in GaAs/AlGaAs heterostructures: Acoustical studies

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Abstract. Electron density and high-frequency (hf) hopping conductivity of two-dimensional electron gas (2DEG) in SI δ-doped GaAs/AlGaAs heterostructures are studied by acoustic methods. In the quantum Hall regime at small filling factors both quantities appear dependent on the cooling procedure, characterized by an initial temperature T_0 of a fast cooling to 4.2 K by immersing into liquid He. These facts are interpreted assuming that T_0 is the freezing temperature for the conductivity of the δ-layer which supplies electrons to 2D channel.

Introduction

Acoustical studies of heterostructures in the quantum Hall regime allow one to determine their high-frequency conductivity, $\sigma_{xx}(\omega)$, as a function of magnetic field. At large half-integer filling factors, when the electron states at the Fermi level are extended, $\sigma_{xx}(\omega)$ does not differ from that measured in a conventional direct-current experiment, $\sigma_{xx}^{dc} \equiv \sigma_{xx}(0)$ [1]. However, the difference is enormous at small filling factors, or near the middle points of developed Hall's plateaus where σ_{xx}^{dc} is extremely small while both real and imaginary parts of $\sigma_{xx}(\omega) \equiv \sigma_1(\omega) - i\sigma_2(\omega)$ are noticeable [2]. They can be determined from simultaneous measurements of attenuation and velocity of a surface acoustic wave (SAW) propagating along the interface and interacting with 2DEG. The experiment [2] evidenced that $\sigma_2 \gg \sigma_1$. This fact, along with the observed temperature and frequency dependences of σ_1 and σ_2, lead to a conclusion that the conductance is due to electron hopping between two local minima of a random impurity potential spaced by a distance smaller that the average correlation length of the latter, see [3]. Another important feature of δ-doped GaAs/AlGaAs heterostructures is that near the centers of the Hall plateaus the 2D channel appears to be considerably shunted by a Si δ-layer which supplying the carriers to the channel [4].

Our previous experiments with different samples have shown that near the Hall plateaus centers both the SAW attenuation, Γ, and the velocity variation, $\Delta V/V$, are poorly reproducible. Namely, the values of σ_{xx} measured in different experiments may vary by several times. At the same time, the quantities measured either in low magnetic fields, or at half-integer filling factors do not differ by more than 20%. We believe that the lack of reproducibility is due to different cooling procedures from room temperature to 4.2 K. In the present work we study this phenomenon systematically.

Experimental results and discussion

We have measured the attenuation coefficient, Γ, and variation of the sound velocity, $\Delta V/V$, of a SAW as function of magnetic field $H \leq 7$ T in a GaAs/AlGaAs heterostructure with the sheet density $n_s \approx 1.4 \times 10^{11}$ cm^{-2}. The measurement were performed for SAW frequencies, 30 and 150 MHz, at two temperatures, 4.2 and 1.5 K. The details of the experimental method, as well as the way to extract $\sigma_{xx}(\omega)$ from measured quantities, are presented in [1, 2, 4]. The cooling process was carefully checked and controlled.

The magnetic field dependences of σ_1 and σ_2 at the frequency 30 MHz are shown in Fig. 1(a) (the raw data for Γ and $\Delta V/V$ are presented in the inset). Acoustic methods at low temperatures require placing the sample in a evacuated chamber, since a cooling liquid causes an extensive SAW absorption. To achieve cooling of a sample attached to a cold finger down to 1.5–4.2 K one needs (after pumping) to fill the chamber with an exchange gas (He^4 at a pressure 0.1 mm Hg). The chamber itself is surrounded with liquid He^4 which can also be pumped to lower the boiling point. Besides, the superconducting solenoid is usually cooled with liquid N_2 before the liquid He^4 being poured into the cryostat.

Fast cooling of a sample is actually accomplished when in the chamber there is the exchange gas and the chamber itself is immersed in the liquid helium. To vary the cooling procedure the sample was pre-cooled to a certain temperature, T_0, with the aid of cool He^4. After the sample chamber was quickly immersed into the liquid helium. This pre-cool temperature, T_0, was measured with a carbon resistor.

Magnetic field dependences of σ_1 in the region 2–4 T for different T_0 are presented in Fig. 1(b). The minima of the curves correspond to the filling factor $\nu = 2$. It follows that the variation of the cooling procedure influences both the minimum position and the minimal value, σ_{min}, of σ_1.

The dependence of σ_{min} on the pre-cool temperature T_0 is shown in Fig. 2(a). It follows

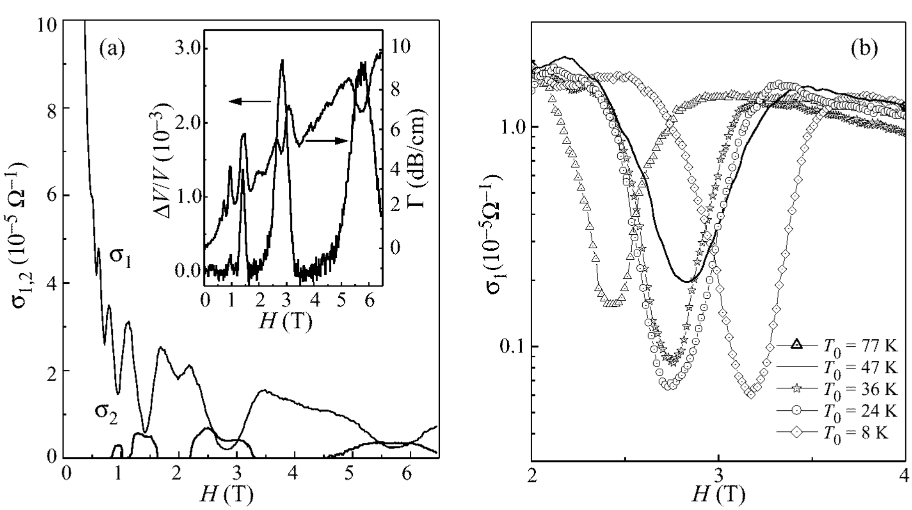

Fig. 1. (a) Dependences of the hf-conductivity components σ_1 and σ_2 on the magnetic field H. $T = 1.5$ K, $f = 30$ MHz. Inset: magnetic field dependences of the SAW attenuation, Γ, and of the relative velocity change $\Delta V/V$, $T = 1.5$ K, $f = 30$ MHz. (b) Magnetic field dependences of σ_1 for $H = 2-4$ T and different initial temperatures, T_0. $T = 1.5$ K, $f = 30$ MHz.

that $\sigma_{\min}$ is an increasing function of T_0. The effective 2DEG density determined from the equation $\nu = 2$ for the minimum position is shown in Fig. 2(b). It is a *decreasing* function of T_0. The results for $\nu = 1$ are similar to those mentioned above.

For the case of $T_0 = 77$ K, time dependences of $\Gamma(H)$ and $\Delta V(H)/V$ have also been monitored. After the sample has been cooled, the measurements were performed every second hour during 28 hours. No changes in both quantities were observed. However, this cooling process proved to be quite reversible. If one takes a sample previously cooled to 4.2 K from, say, $T_0 = 8$ K, heats it back to 24 K, and then cools it again to 4.2 K, one obtains the same experimental values of Γ and $\Delta V/V$ as they were at 4.2 K in the preceding cooling cycle.

We believe that the aforementioned results are consistent with our previous conclusion [4] regarding an important role of hf-conductance through δ-layer in the situation when the electron states in the 2D-channel are localized.

To explain qualitatively the observed behavior let us analyze δ-layer contribution to σ_1. Since the electron density in the 2D-channel is about 10 times smaller than the impurity density in the δ-layer, to the lowest approximation one can consider the latter as being isolated from the channel. Because of the same reason, at low temperatures, the electron Fermi level in the δ-layer is located above the density-of-states maximum. Thermal ionization of some impurities leads to its shift *downwards*, i. e. to the region of *larger* density of states. Now, let us assume that the initial electron energy distribution at $T = T_0$ is *quenched* due to electron trapping and does not change during subsequent cooling. Then we immediately arrive at the conclusion that the Fermi-level density of states, and consequently σ_1, are *increasing* functions of T_0. The observed decrease in the 2D-channel density with increase of T_0 can be also explained as caused by an additional thermally-induced electron trapping in the δ-layer which is also quenched at $T \leq T_0$. Thus the above assumptions are consistent with Figs. 2(a) and 2(b).

We have employed the method [4] to extract the "hopping" contribution of the 2D-channel. It appears almost independent of T_0 and equal to $(2.7 \pm 0.6) \times 10^{-8}\,\Omega^{-1}$. The electron localization length calculated from this value is $\xi = 2.6 \times 10^{-6}$ cm which is slightly greater than the magnetic length 1.6×10^{-6} cm for $H \approx 2.8$ T. Note that σ_1 at

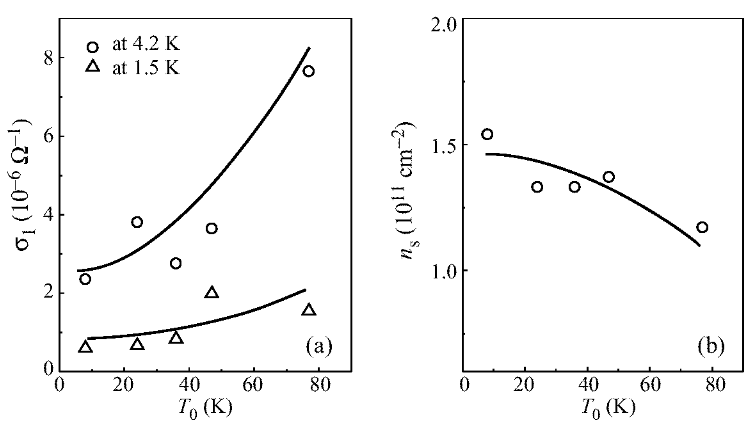

Fig. 2. The experimental dependencies of real part of hf-conductivity σ_1 (a) and sheet density (b) on T_0 at filling factor $\nu = 2$ at $T = 1.5$ K and 4.2 K. $f = 30$ MHz.

half-integer filling factors, within the experimental error appears to be independent of the cooling procedure.

Conclusion

We conclude that hf-conductance of δ-doped GaAs/AlGaAs heterostructures is sensitive to the cooling procedure, and a proper control of the latter is important.

Acknowledgments

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